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AFFDL-TR-79-3006

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X-RAY DIFFRACTION MEASUREMENTS OF CRACK TIP STRESSES AS A CRACK ADVANCES THROUGH A SINGLE OVERLOAD AFFECTED ZONE

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Structural Integrity Branch
Structures and Dynamics Division

March 1979

TECHNICAL REPORT AFFDL-TR-79-3006

Final Report for Period November 1977 to July 1978

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20060921225

NOTICE

This technical report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFFDL-TR-79-3006	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) X-RAY DIFFRACTION MEASUREMENTS OF CRACK TIP STRESSES AS A CRACK ADVANCES THROUGH A SINGLE OVERLOAD AFFECTED ZONE		5. TYPE OF REPORT & PERIOD COVERED Final Report for Period November 1977 to July 1978 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Donald R. Holloway, Capt, USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Flight Dynamics Laboratory (AFFDL/FBE) Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Project 2307 Task 2307N1 Work Unit 2307N101
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE March 1979 13. NUMBER OF PAGES 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Stress measurement, X-ray diffraction, Crack growth retardation, Residual stresses, Crack tip

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Stress levels were measured in the vicinity of a crack tip using an x-ray diffraction technique to determine the correlation of these measurements with crack closure and residual stress theories. A single tensile overload was applied to a modified compact specimen of 1020 steel. The material had been heat-treated to obtain an ASTM grain size of 10 to 11 and a yield strength of 70 ksi. Crack tip residual stresses were measured in the unloaded condition and crack tip applied stresses were measured under load. These measurements were made as the

20. Abstract (Continued)

crack was extended into and past the overload affected zone. Results suggested that overload retardation was primarily due to residual compressive stresses generated at the point of overload. It was observed that the effect of the overload had dissipated by the time the crack was propagated through a distance approximately equal to the plastic zone caused by the overload.

FOREWORD

This report is the result of an in-house effort under Project 2307, "Flight Vehicle Dynamics," Task 2307N1, "Research on the Behavior of Metallic and Composite Components of Airframe Structures," Work Unit 2307N101, "Structural Integrity Research." The work was conducted in the Air Force Flight Dynamics Laboratory, Structures and Dynamics Division, Structural Integrity Branch, (AFFDL/FBE), at Wright-Patterson Air Force Base, Ohio. The research was conducted by Capt. D. R. Holloway and Capt. J. E. Allison from November 1977 through July 1978.

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SECTION I

INTRODUCTION

Extensive investigations (Reference 1-5) have been conducted in an attempt to explain the phenomenon of crack growth retardation resulting from tensile overloads. These investigations have resulted in proposals of several crack growth retardation theories. In general, these theories attribute delayed retardation behavior to crack closure (Reference 6), residual stresses (Reference 7), or a combination of these mechanisms.

The crack closure theory suggests that the delay in fatigue crack growth is caused by the formation of a zone of residual tensile deformation left in the wake of a propagating crack. This deformation causes the crack to remain closed during a portion of the applied tensile load cycle. Consequently, fatigue crack growth delay occurs because only the portion of the tensile load cycle that is above the crack opening level is effective in extending the crack.

The residual stress theory is similar to the crack closure theory except that it attempts to account for crack growth based on the actual forces acting at the crack tip. This theory suggests that the application of a high tensile load cycle forms residual compressive stresses in the vicinity of a crack tip that reduce the rate of fatigue crack growth. These residual compressive stresses are the result of a reverse plastic zone created after a remote tensile stress has been removed.

A first step toward understanding the more complex phenomenon of fatigue crack propagation under spectrum loading involves a fundamental understanding of delay under single and intermittent overloading conditions (Reference 5, 8-10). The objective of this investigation was to measure and study the distribution of crack tip stresses and to determine the correlation of these measurements with the crack closure and residual stress theories.

This report describes the experimental test procedure and discusses the results of stress measurements at a crack tip as a crack was extended into and past a single overload affected zone. Stress distributions in the vicinity of a crack tip were measured using x-ray diffraction techniques. Residual stresses were measured in the unloaded condition while applied stresses were measured at the baseline stress intensity.

SECTION II

TEST INFORMATION

1. SPECIMEN MATERIAL AND GEOMETRY

The primary constraint governing material selection was suitability for use with the x-ray diffraction equipment. One factor to be considered was the relatively large size of the x-ray beam spot used (0.025 inch diameter on the specimen surface). Another important consideration was the small size of the plastic zone produced by a single overload. Equally important was the grain size of the metal being studied. If the grain size is large relative to the x-ray beam size, it can lead to major errors, in that the results will depend on those particular grains making a large contribution to the diffraction peak. Small grain sizes ensure the stress measurements will be averaged across many grains rather than just a few grains.

With the above considerations in mind a 1020 steel was selected for the investigation. This plain carbon steel alloy was heat-treated to obtain an ASTM grain size of 10 to 11 and a yield strength of approximately 70 ksi. With this heat-treatment the requirements for a small grain size were met. The low value of yield strength ensured the plastic zone would be "large" for normal loads.

The specimen geometry chosen for the test was a modified compact crack growth specimen cut to a size 3.86 by 3.00 inches from a 0.25 inch thick plate. The specimen thickness was reduced to 0.233 inch after a decarburized region was removed by grinding. Specimen geometry and dimensions are shown in Figure 1.

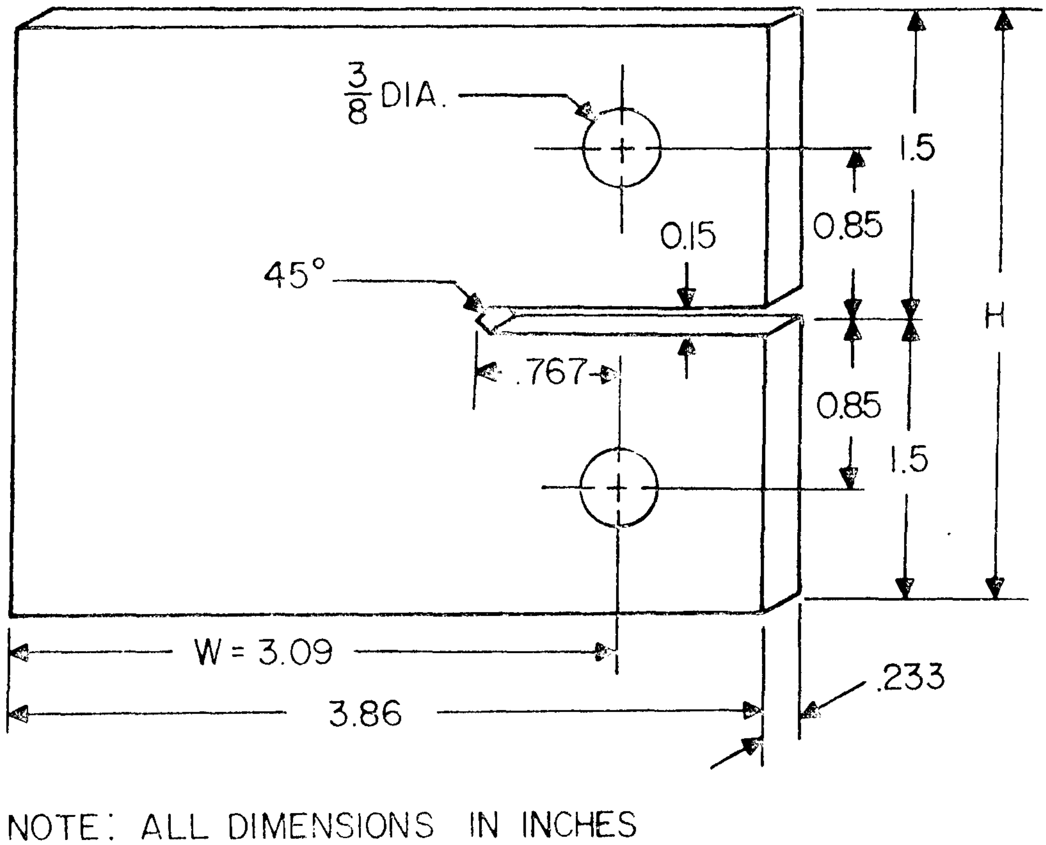

Figure 1. Modified Compact Specimen

2. STRESS INTENSITY FOR MODIFIED COMPACT SPECIMEN

The stress intensity factor equation for a modified compact crack growth specimen can be presented in the form

$$K = \frac{P}{B\sqrt{a}} f\left(\frac{a}{W}\right) \qquad (1)$$

where K is the opening mode stress intensity, P is the applied load, B is the thickness of the specimen, a is the measured crack length, and f(a/W) is the geometric correction factor. For a specimen with a constant ratio of specimen height to specimen width, the function f(a/W) can be expressed in a polynomial form as a function of the dimensionless crack length a/W. For the modified compact specimen having H/W = 0.972 (Figure 1) the f(a/W) can be presented as

$$f\left(\frac{a}{W}\right) = 30.96\left(\frac{a}{W}\right) - 195.8\left(\frac{a}{W}\right)^2 + 730.6\left(\frac{a}{W}\right)^3 - 1186.3\left(\frac{a}{W}\right)^4 + 754.6\left(\frac{a}{W}\right)^5 \qquad (2)$$

In the range $0.25 < a/W < 0.75$, the polynomial is accurate to within 0.5 percent (Reference 11).

3. TEST APPARATUS

All stress measurements were taken using the FASTRESS* x-ray stress analyzer manufactured by the American Analytical Corporation. This equipment contains two x-ray diffraction goniometers, each having a chromium x-ray tube and a two geiger

*Trademark of General Motors Corporation tube x-ray detection device. The FASTRESS measures stress by comparing the output of the two geiger tubes. The geiger tubes are physically driven through the diffraction cone by a servo-controlled system. When the output of each geiger tube is balanced with the other, it is assumed the diffraction peak is midway between their centers. In the FASTRESS the angular distance between the geiger tube centers is adjustable. For the measurements made on the 1020 steel specimen, the centers were set at 2.5 degrees for the ψ = 0 degree and the ψ = 45 degree peaks. Chromium radiation was used as the x-ray source which makes a diffraction peak with ferritic steel at an angle 2θ of 156.2 degrees with the 211 crystallographic plane. The voltage for the x-ray tubes was set to 35 KVP and the current was nominally 10 ma. A special collimator was used to produce an 0.025 inch diameter x-ray spot on the specimen. A stress factor of 86.6 ksi/degree was calculated from Equation 3. The bulk elastic properties for steel alloy materials, 30 X 10^6 psi elastic modulus and 0.3 Poisson's Ratio, were assumed for the stress calculations.

$$S = \frac{\cot \theta}{2} \cdot \frac{E}{1+\nu} \cdot \frac{1}{\sin^2\psi} \qquad (3)$$

where S = Stress factor

θ = X-Ray incidence angle

E = Bulk modulus of elasticity

ν = Poisson's Ratio

ψ = X-Ray diffraction angle

The FASTRESS x-ray head was mounted on a traveling stage so it could be moved in increments of 0.001 inch in the X, Y, and Z directions in order to position the focal spot of the x-ray unit. The distance between two measurements was normally 0.025 to 0.050 inch depending on the stress gradient. Each stress measurement took approximately two minutes; measurement of an entire stress profile required about an hour.

4. TEST PROCEDURE

Precracking and crack growth were accomplished on a servo-hydraulic, closed loop, 10,000 pound cyclic loading machine. The specimen was precracked to a length of 1.118 inches at a constant maximum stress intensity of 23.1 ksi $\sqrt{in}$ and a load ratio of 0.1. The value 23.1 ksi $\sqrt{in}$ was arbitrarily chosen and will be referred to as the baseline level in the remainder of the paper. The load levels were controlled so that the maximum stress intensity was held to plus or minus two percent.

Crack tip residual and applied stress distributions were measured prior to and after the application of a tensile load which produced a stress intensity of 46.2 ksi $\sqrt{in}$, hereafter referred to as the overload. For stress measurements the specimen was placed in a load frame where measurements were taken without (residual stresses) and with (applied stresses) load.

For the first two sets of stress profile measurements the x-ray beam was located near the crack tip by visual alignment. Stress measurements were made in the crack tip area to find the maximum stress. This point was assumed to be the crack tip. This procedure proved to be time consuming so a telemicroscope was mounted to the x-ray head with the cross-hairs fixed on the beam spot. Using this procedure the crack tip could readily be found and repeatable positioning of the x-ray beam spot was ensured.

After crack tip stress measurements were made, the specimen was placed again in the cyclic test machine to extend the crack. When the crack was grown to a desired length, the specimen was placed again in the load frame and stress levels were measured using x-ray diffraction methods. This process of growing the crack to a desired length and measuring the stress levels was repeated several times as the crack was propagated into and past the overload affected zone.

SECTION III

EXPERIMENTAL RESULTS AND DISCUSSION

1. EXPERIMENTAL RESULTS

Crack tip residual stress distributions were measured prior to and after a tensile load (2500 pounds) which produced a stress intensity of 46.2 ksi $\sqrt{in}$, hereafter referred to as the overload. The resulting distributions are shown in Figure 2. The compressive stress distribution caused by the application of the overload is very evident. Also observed is a region of tensile stress behind the crack tip similar to that noted by Allison (Reference 12).

Comparing the residual stress profiles before and after the overload, it can be seen that the crack tip residual stresses after the overload are significantly reduced (i.e., more compressive) from those prior to the overload. Upon application of a 1250 pound load (baseline stress intensity) measurements indicated that all stresses in front of and behind the crack tip were tensile (Figure 3).

Further insight into the retardation process was attempted by measuring residual and applied stress profiles after the crack was propagated into and through the overload affected region. The specimen was cyclically loaded again under constant amplitude conditions at a load ratio of 0.1 to extend the crack 0.054 inch (total crack length was 1.172 inches). Residual and applied stress measurements were made again.

Comparing the crack tip residual stress distributions before and after crack extension (Figure 4), it can be seen that the stress profile caused by the overload was essentially undisturbed by crack extension. At the baseline

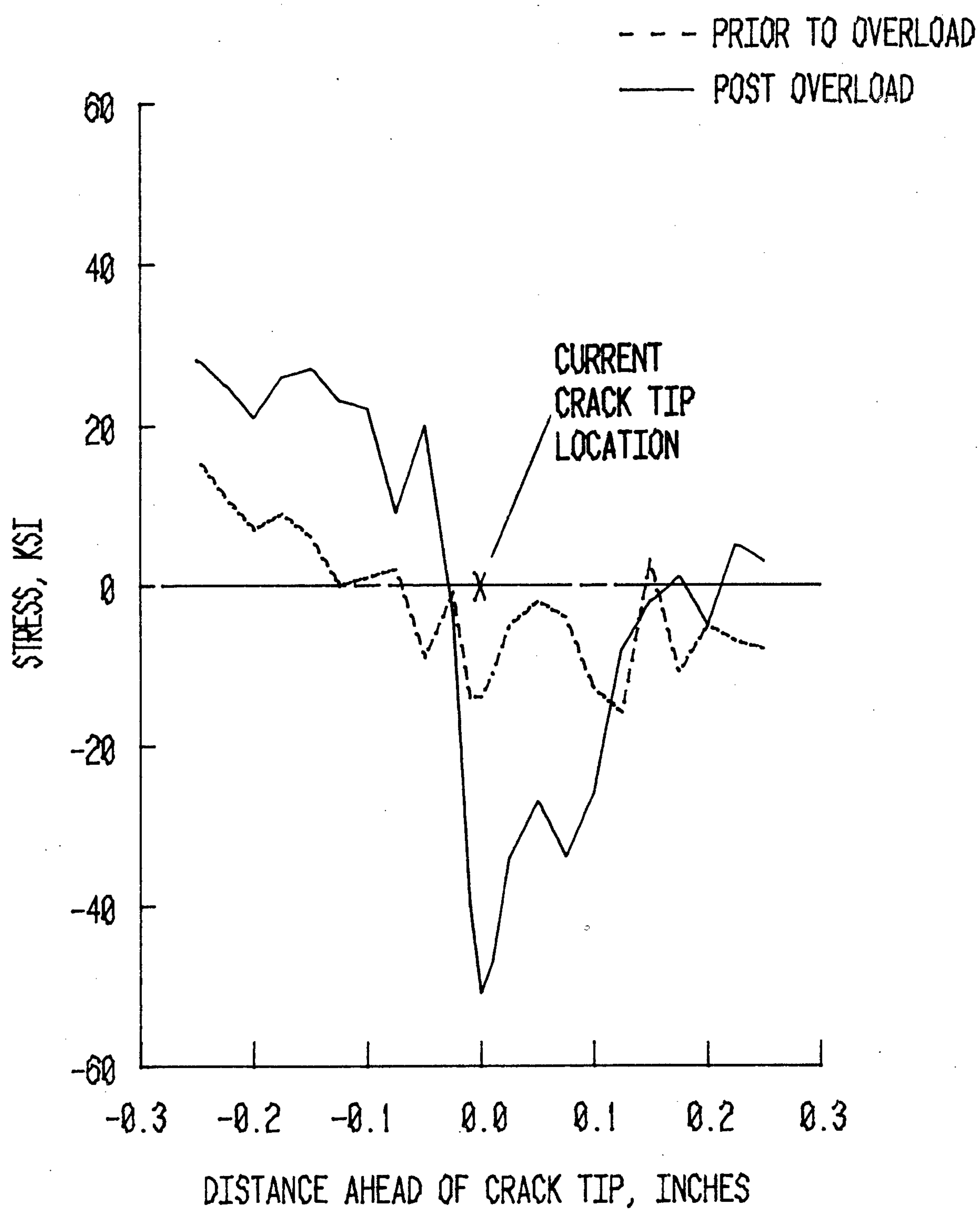

Figure 2. Residual Stress Profile Before and After 46.2 ksi $\sqrt{in}$ Overload

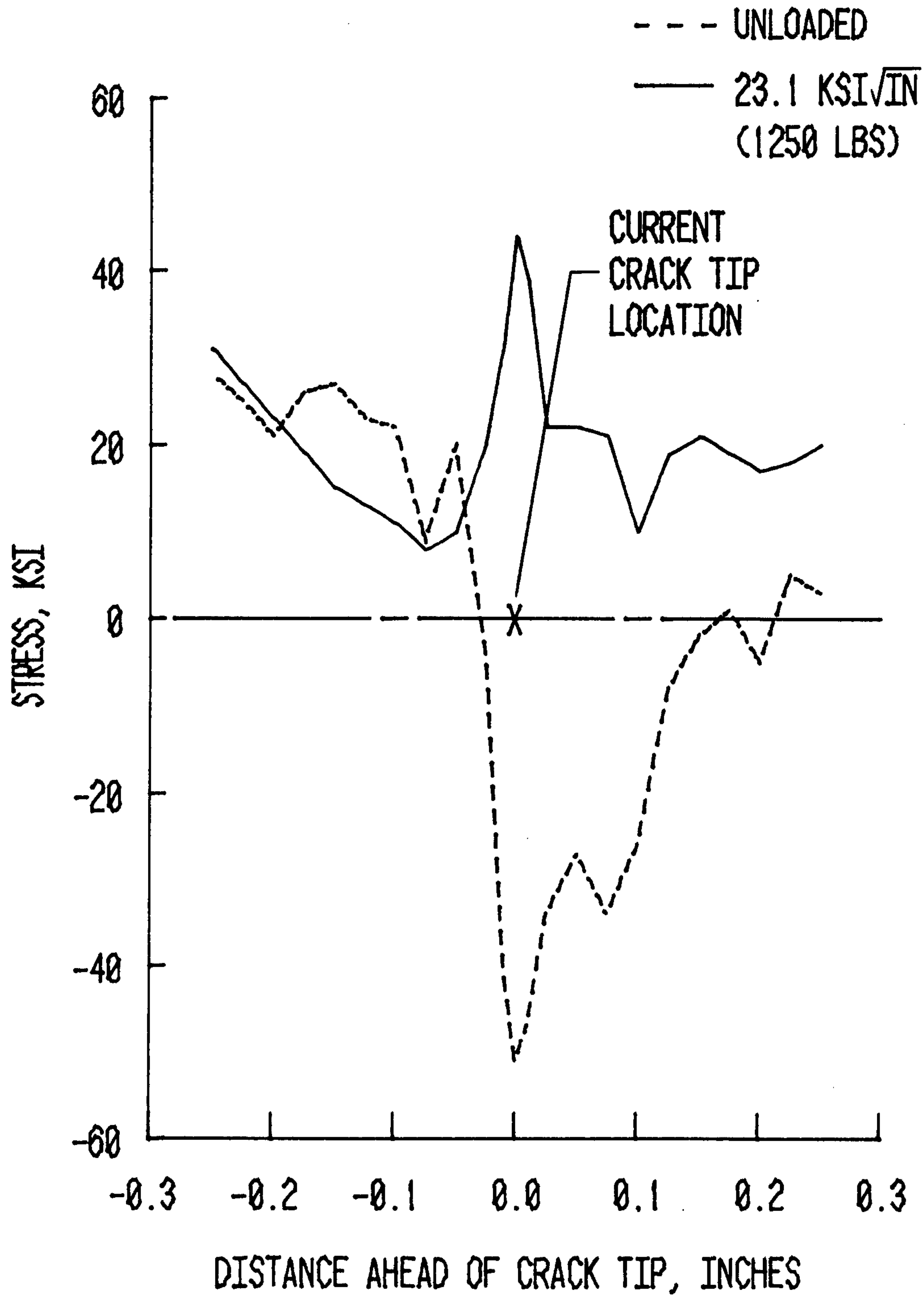

Figure 3. Stress Profiles After 46.2 ksi $\sqrt{in}$ Overload

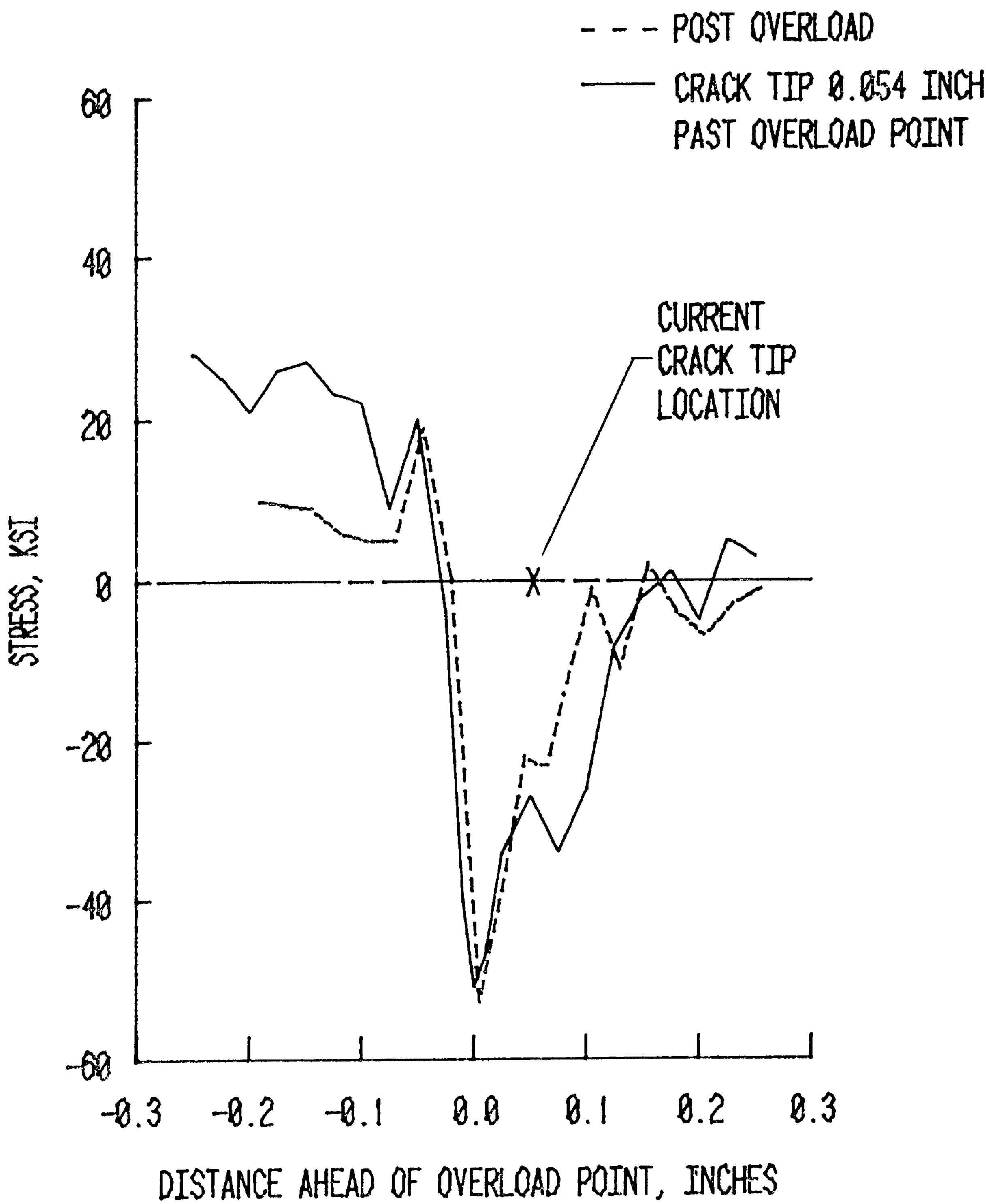

Figure 4. Residual Stress Profiles After 46.2 ksi $\sqrt{in}$ Overload and After Crack Extension of 0.054 Inch Past Point of Overload

stress intensity conditions (1170 pounds), the crack tip applied stress profile (Figure 5) shows portions of the material behind the extended crack to be in compression, whereas the material immediately ahead of the crack tip is found to be in tension.

Additional crack growth of 0.057 inch put the crack tip 0.111 inch past the overload application point (total crack length was 1.229 inches). Figure 6 shows a comparison of the residual stress profiles prior to and after the additional crack growth. The maximum residual compressive stress was found to be reduced upon crack extension while stresses behind and in front of the point of overload remained essentially the same. Again load (1150 pounds) was applied to bring the stress intensity to the baseline condition. Figure 7 shows the region associated with the overload application point again to be in compression. Tensile stresses were found in front of and immediately behind the crack tip.

Again the specimen was cyclically loaded to extend the crack. The crack was propagated 0.154 inch placing the crack tip 0.265 inch past the overload point (total crack length was 1.383 inches). Comparing the residual stress measurements after additional crack growth with the previous measurements (Figure 8) shows the maximum compressive stress to again decrease in magnitude. As with all previously applied stress measurements at the baseline stress intensity, Figure 9 shows the region associated with the overload point to be in compression, while tensile stresses are found immediately behind and in front of the crack tip.

The final crack growth was an attempt to bring the crack growth rate back up to the crack growth rate prior to the overload. However, after additional crack growth of 0.432 inch, or 0.697 inch past the point of overload application

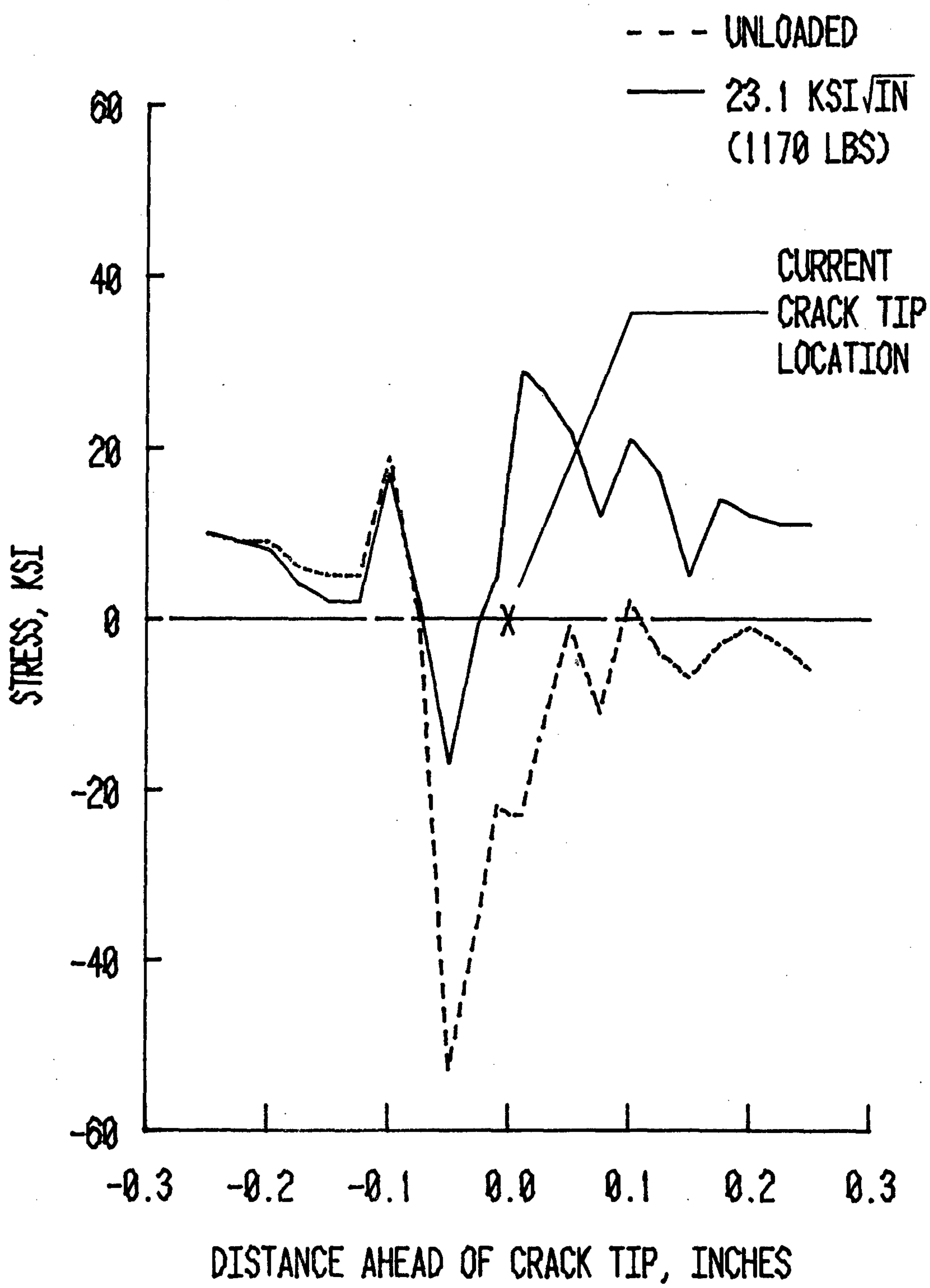

Figure 5. Stress Profiles After Crack Extension of 0.054 Inch Past Point of Overload

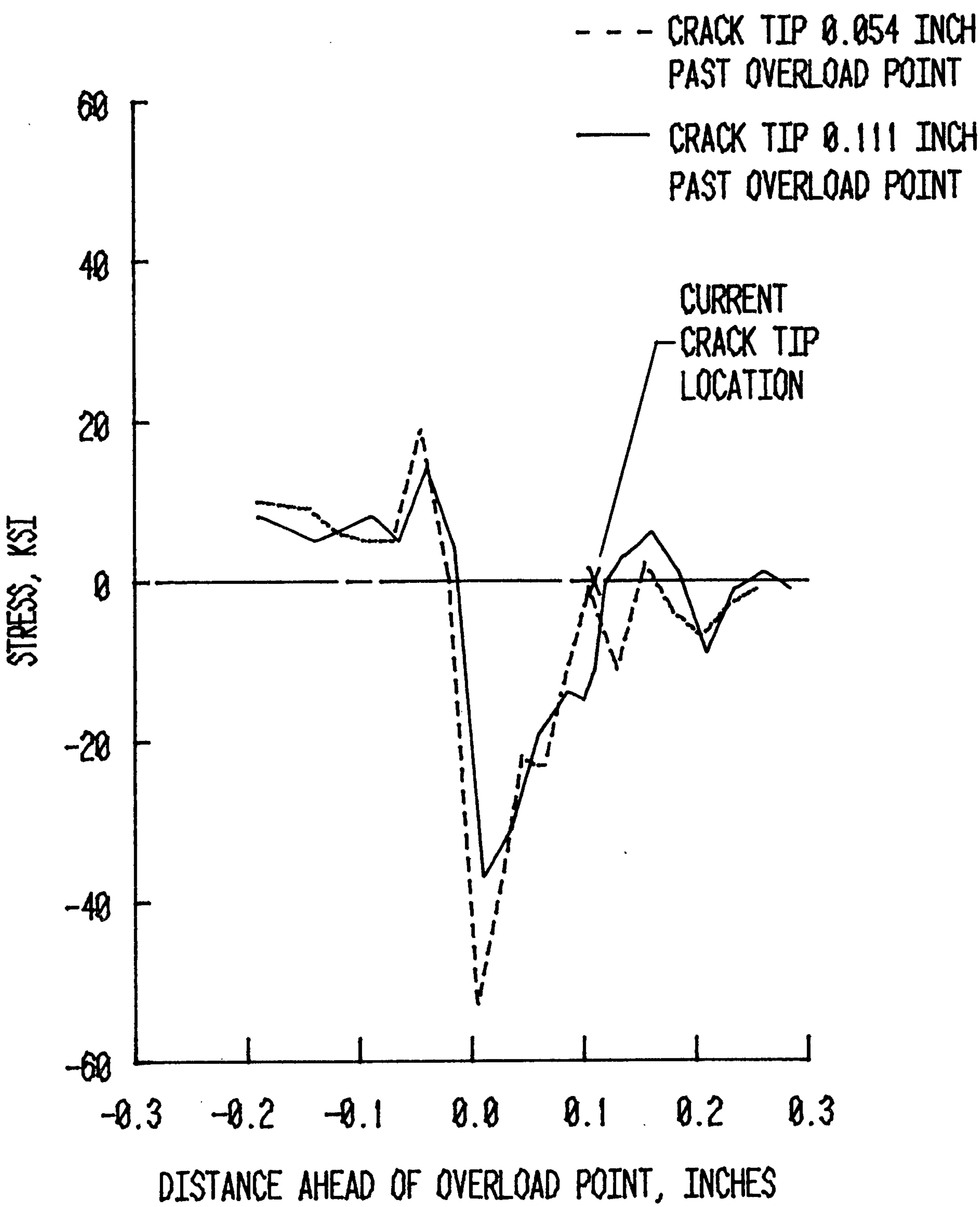

Figure 6. Residual Stress Profiles After Crack Extensions of 0.054 and 0.111 Inch Past Point of Overload

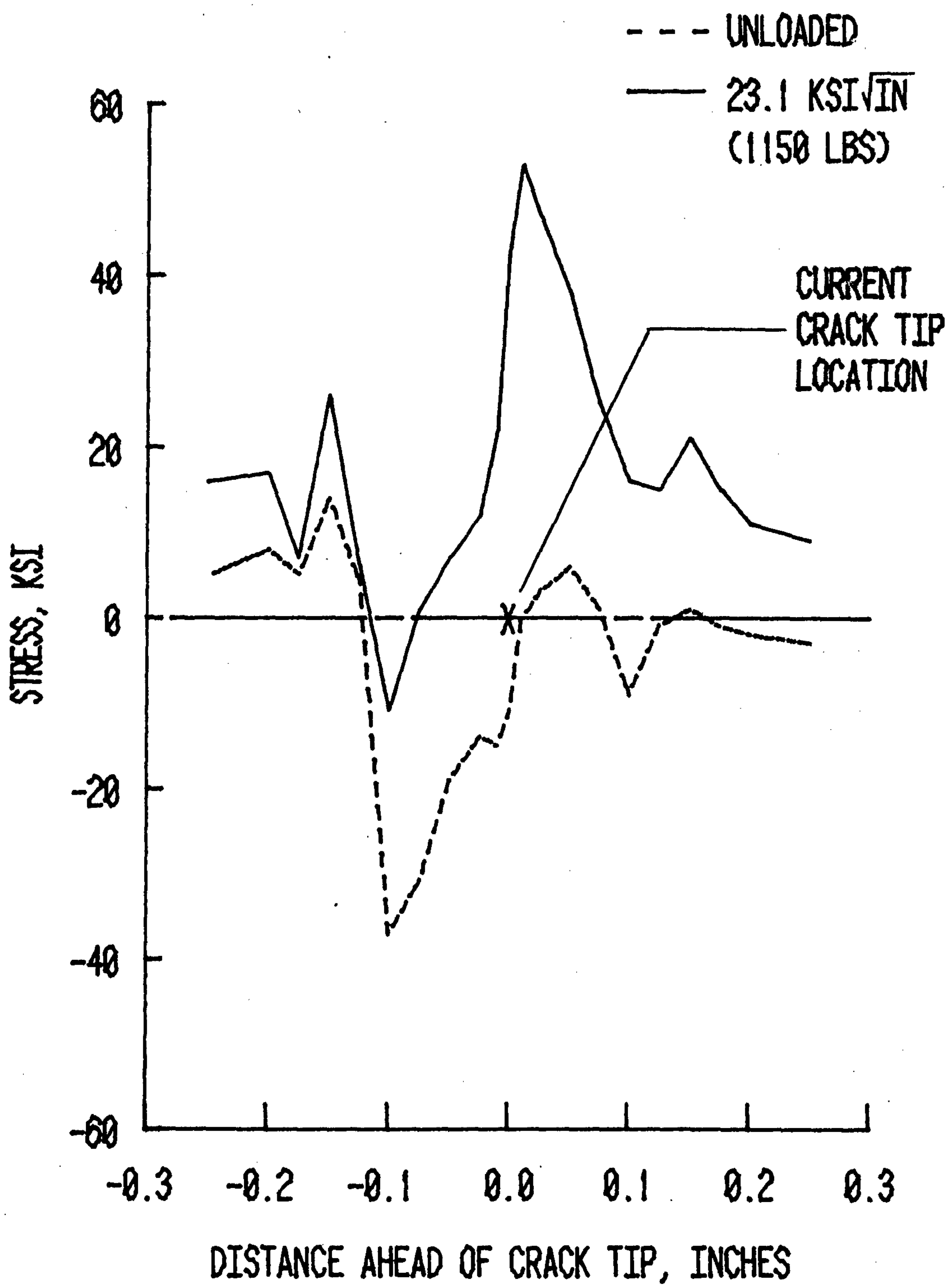

Figure 7. Stress Profiles After Crack Extension of 0.111 Inch Past Point of Overload

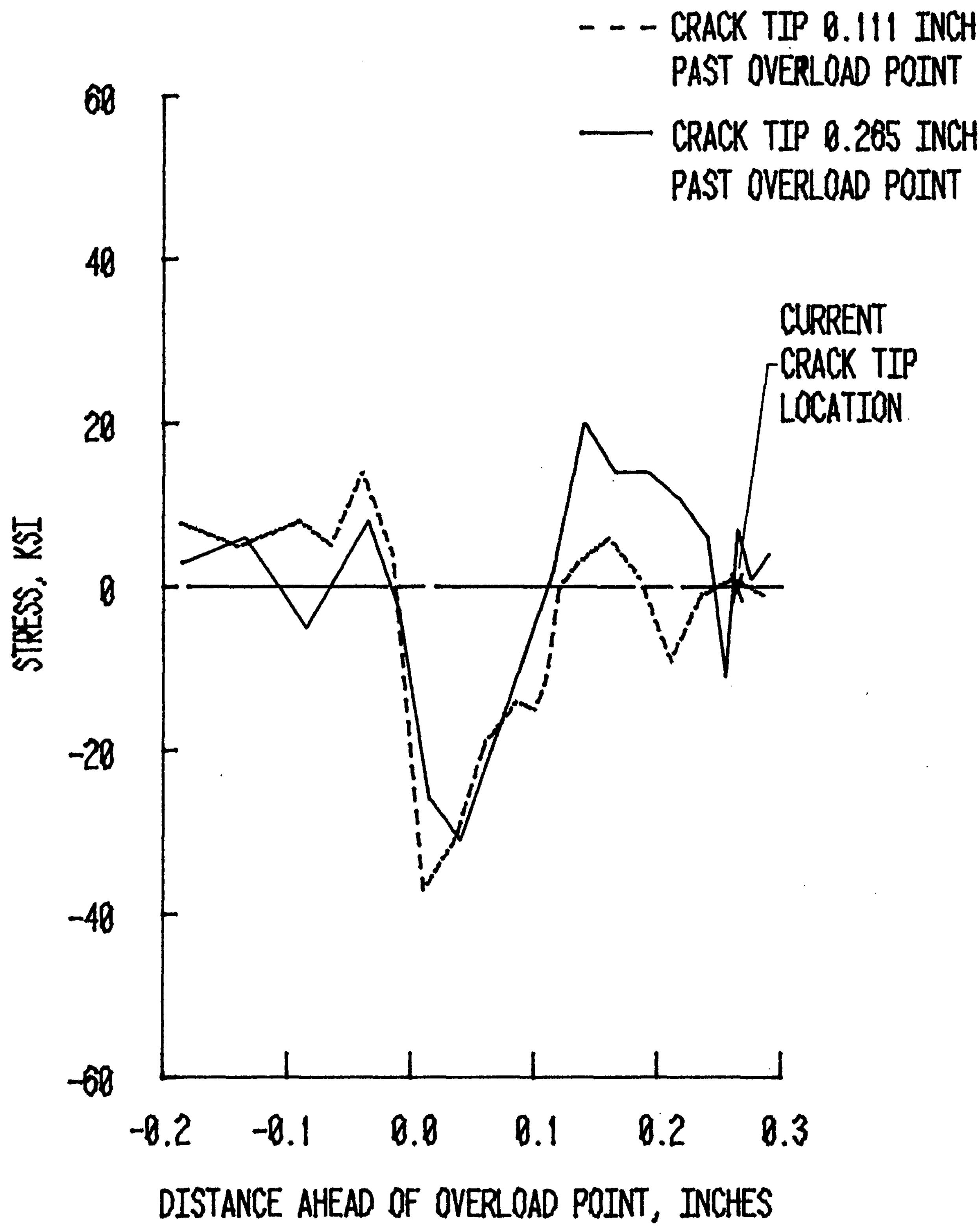

Figure 8. Residual Stress Profiles After Crack Extensions of 0.111 and 0.265 Inch Past Point of Overload

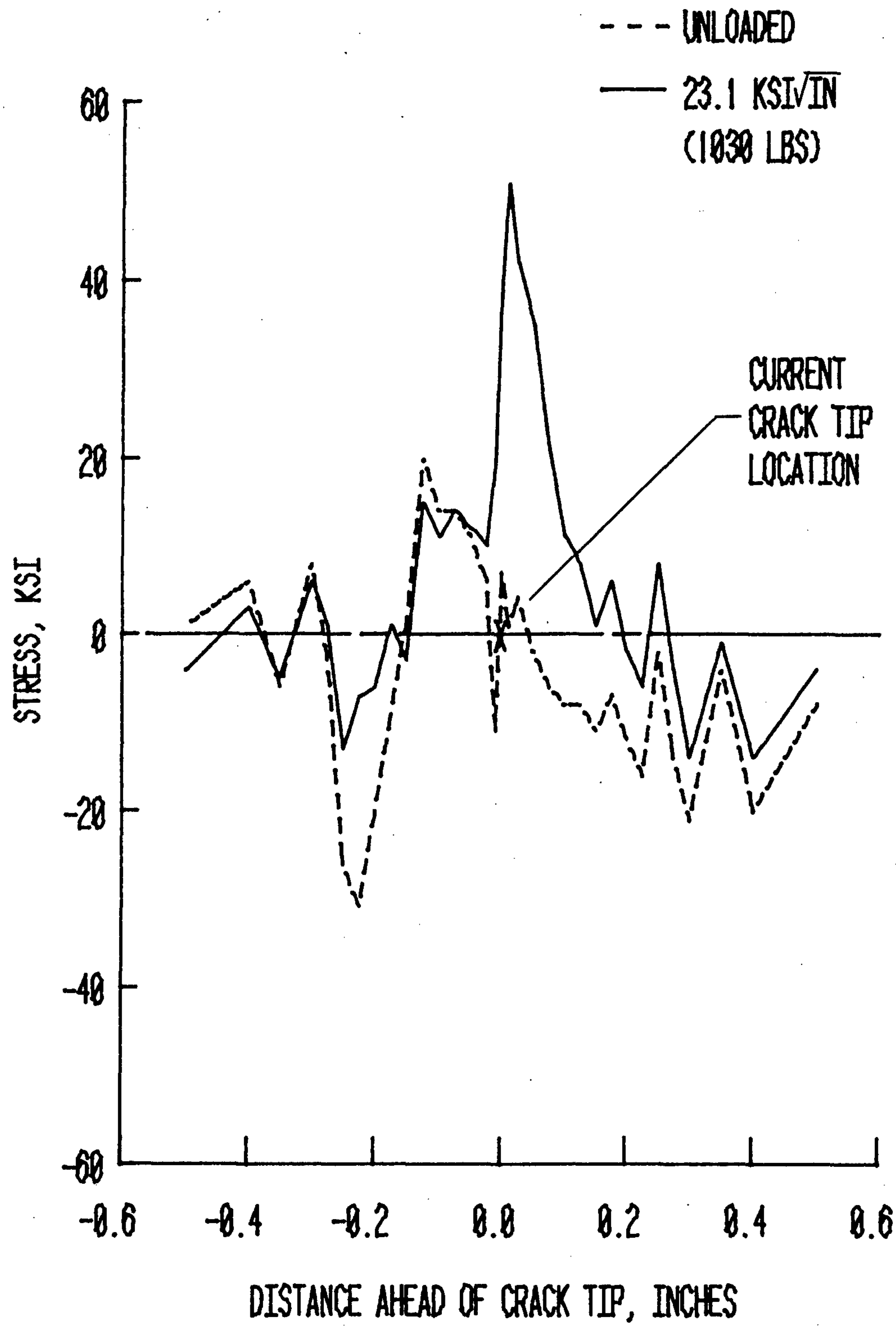

Figure 9. Stress Profiles After Crack Extension of 0.265 Inch Past Point of Overload

(total crack length was 1.815 inches), the crack growth rate was still less than the crack growth rate prior to overload. At this point a decision was made to stop further crack growth and to proceed with final stress measurements.

Residual and applied stress measurements showed similar results as with previous measurements. The region associated with the point of overload again showed a decrease in residual compressive stress (Figure 10). At the baseline stress intensity condition , i.e., 700 pounds, (Figure 11), tensile stresses were noted again immediately behind and in front of the crack tip. Compressive stresses were found again in the region associated with the overload application point.

2. DISCUSSION OF RESULTS

Crack tip stress distributions were measured prior to and after a tensile overload had been applied. A region of residual compressive stresses resulting from the overload was very evident. This region of compressive stresses remained throughout the investigation as the crack was propagated into and past the overload affected zone. The maximum residual compressive stress associated with the point of overload application was observed to slightly decrease with each crack extension. This zone of residual compressive stresses lends credence to the retardation theory based on residual stresses.

Upon application of a load to the baseline stress intensity, the region associated with the point of overload application remained in compression with each crack extension. Tensile stresses were observed ahead of the crack tip as the crack was propagated into and past the overload affected zone. When the crack tip was grown past the influence of the overload induced plastic zone,

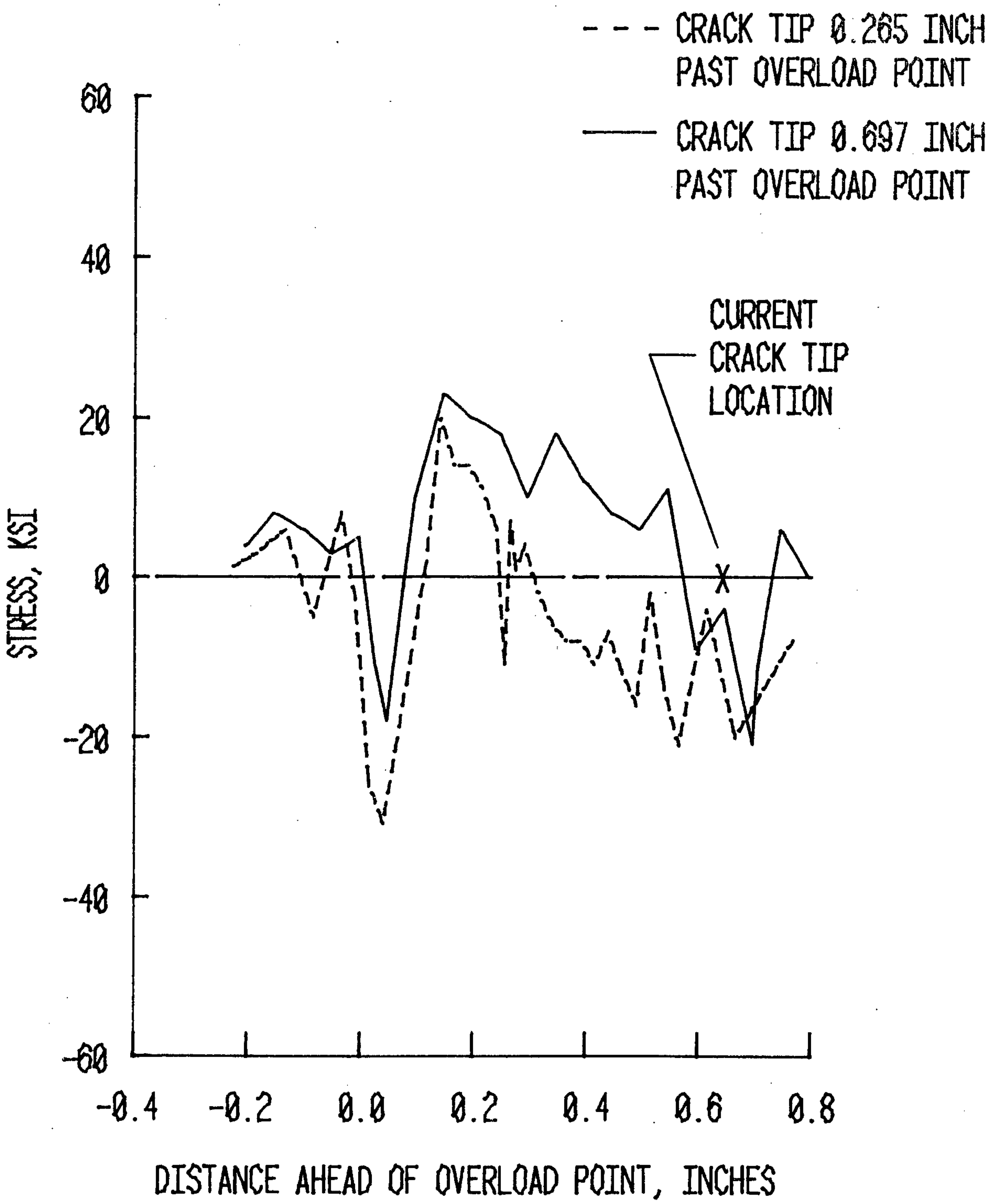

Figure 10. Residual Stress Profiles After Crack Extensions of 0.265 and 0.697 Inch Past Point of Overload

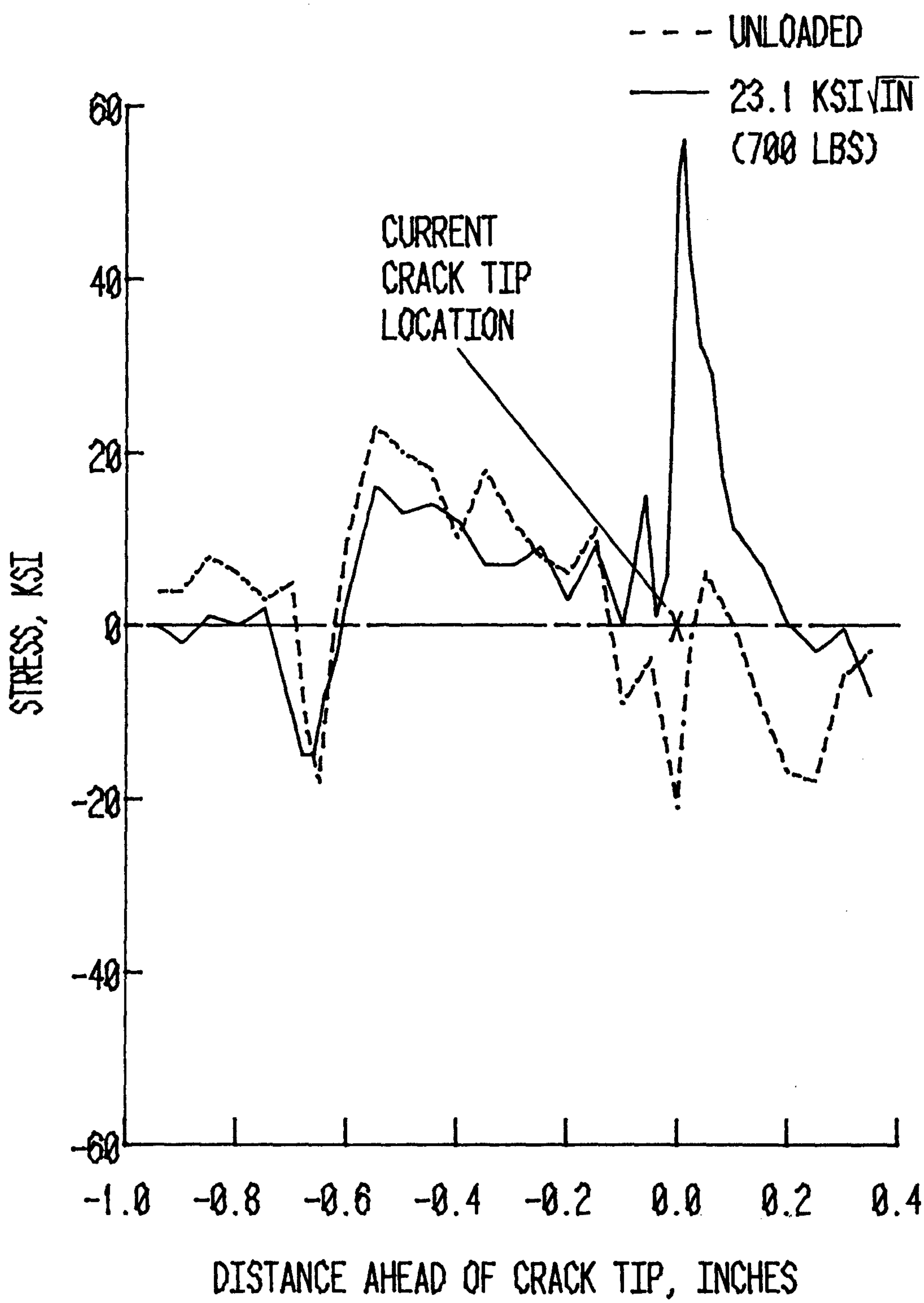

Figure 11. Stress Profiles After Crack Extension of 0.697 Inch Past Point of Overload

tensile stresses were found in the wake of the crack between the overload application point and the crack tip. These findings are in direct contrast with the crack closure concept which suggests that stresses behind a crack tip are compressive in nature.

SECTION IV

CONCLUSIONS

Results obtained from this study suggest that overload retardation is due to residual compressive stresses generated at the point of overload application. This zone of residual compressive stresses was evident with each crack extension.

Stress measurements at the baseline stress condition revealed that the region associated with the point of overload application always remained in compression. When the crack was extended past the influence of the overload induced plastic zone, tensile stresses were found in the wake of the crack. These findings contradict the crack closure concept which suggests that stresses behind a crack tip are compressive in nature.

The main observations of this investigation are summarized in the following paragraphs.

1. Crack tip residual stress distributions were measured prior to and after a tensile overload had been applied. The maximum residual compressive stress, associated with the point of overload application, was observed to decrease with each crack extension.

2. Crack tip applied stress distributions were measured while the specimen was loaded to the baseline stress condition. The maximum crack tip applied stress was found to be at its lowest value when the crack tip was inside the overload affected zone.

3. It was observed that upon loading to the baseline stress intensity condition, the region associated with the overload application point always remained in compression with each crack extension. It was further observed

that material immediately behind and in front of the crack tip produced tensile stresses at each crack extension.

4. It was noted that the effect of the overload dissipated by the time the crack was propagated through a distance approximately equal to the plastic zone caused by the overload.

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